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Diffusion of UHECRs in extragalactic magnetic fields

Rafael Alves Batista, Günter Sigl

II. Institut für Theoretische Physik
Universität Hamburg

rafael.alves.batista@desy.de

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ultra-high energy cosmic rays

open questions

- where do they come from?
- what are they made of?
- how are they accelerated?

problems

- is there a maximum energy they can reach?
- can we see new physics through their interaction?
- where does the transition between galactic and extragalactic cosmic rays take place?

- observables from CR experiments: spectrum, composition, anisotropy
- magnetic field determine the trajectory of particles
- to do UHECR astronomy we need to understand magnetic fields (galactic and extragalactic)
- signatures of magnetic fields and matter distribution may be imprinted in experimental data

diffusion equation in an expanding universe

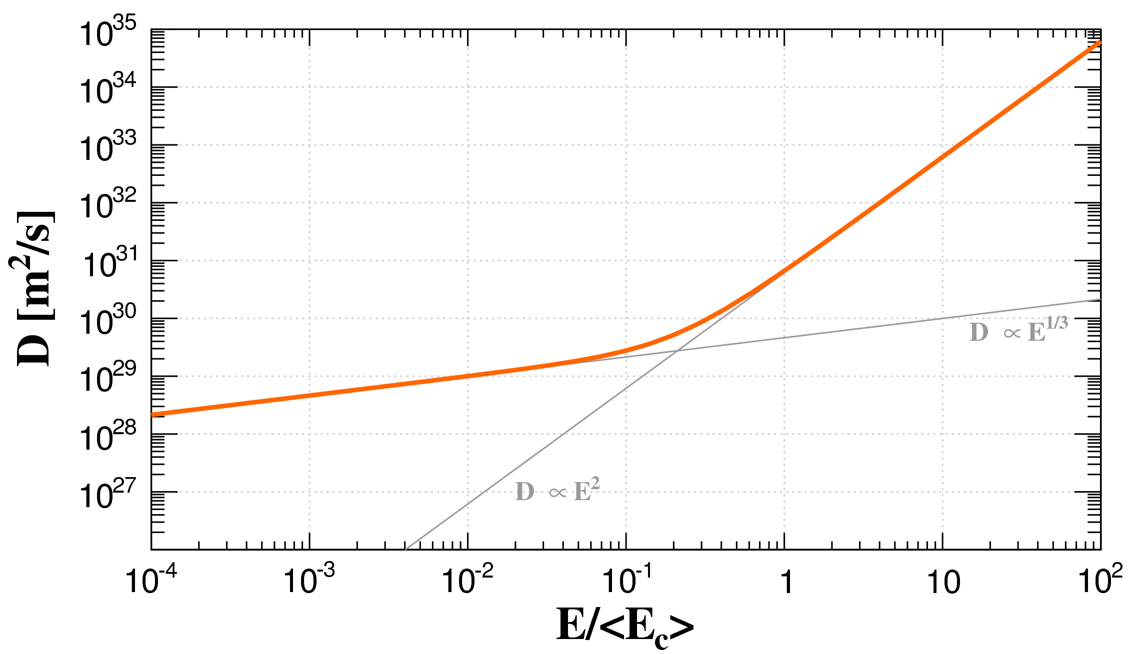
$$\frac{\partial}{\partial t}n(E,\vec{r},t) - b(E,t)\frac{\partial}{\partial E}n(E,\vec{r},t) + 3H(t)n(E,\vec{r},t) - n(E,\vec{r},t)\frac{\partial}{\partial E}b(E,t) - \frac{D(E,t)}{a^2(t)}\nabla^2 n(E,\vec{r},t) = \frac{Q(E,t)}{a^3(t)}\delta^3(\vec{r}-\vec{r_g})$$

$n(E,\vec{r},t)$: number density
$b(E,t)$: energy losses
$D(E,t)$: diffusion coefficient
$H(t)$: Hubble constant
$Q(E,t)$: source term
$a(t)$: scale factor

Berezinsky & Gazizov ApJ 643 (2006) 08

diffusion coefficient

$$D(E,z,B) = \frac{cl_c}{3}\left[a_L\left(\frac{E}{E_c}\right)^{\frac{1}{3}} + a_H\left(\frac{E}{E_c}\right)^2\right]$$



source term

$$Q(E,z) = \frac{\xi_Z f(z) E^{-\gamma}}{\cosh\left(\frac{E}{E_{max}}\right)}$$

γ : spectral index
E_{max} : maximum energy
$f(z)$: evolution function
ξ_Z : fraction of nuclei with charge Ze

energy losses

$$b(E,t) = -\frac{dE}{dt}$$

the diffusive cosmic ray spectrum

$$j_t(E,B) = \sum_{i=1}^{N_s} j_s(E) = \frac{c}{4\pi} \int_0^{z_{max}} dz \left|\frac{dt}{dz}\right| Q(E_g(E,z),z) \frac{dE_g}{dE} \sum_{i=1}^{N_s} \frac{\exp\left(-\frac{r_i^2}{4\lambda^2}\right)}{(4\pi\lambda^2)^{\frac{3}{2}}}$$

$\frac{dt}{dz}$: redshift evolution

$\frac{dE_g}{dE}$: initial/final energy

λ : Syrovatskii variable

$$j(E) = \int_0^{\infty} dB p(B) j_t(E,B)$$

- **spectrum integrated over magnetic field distribution**
- **only adiabatic losses considered**

redshift evolution

$$\left|\frac{dt}{dz}\right| = \frac{1}{H_0(1+z)} \frac{1}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

ΛCDM cosmology

initial/final energy

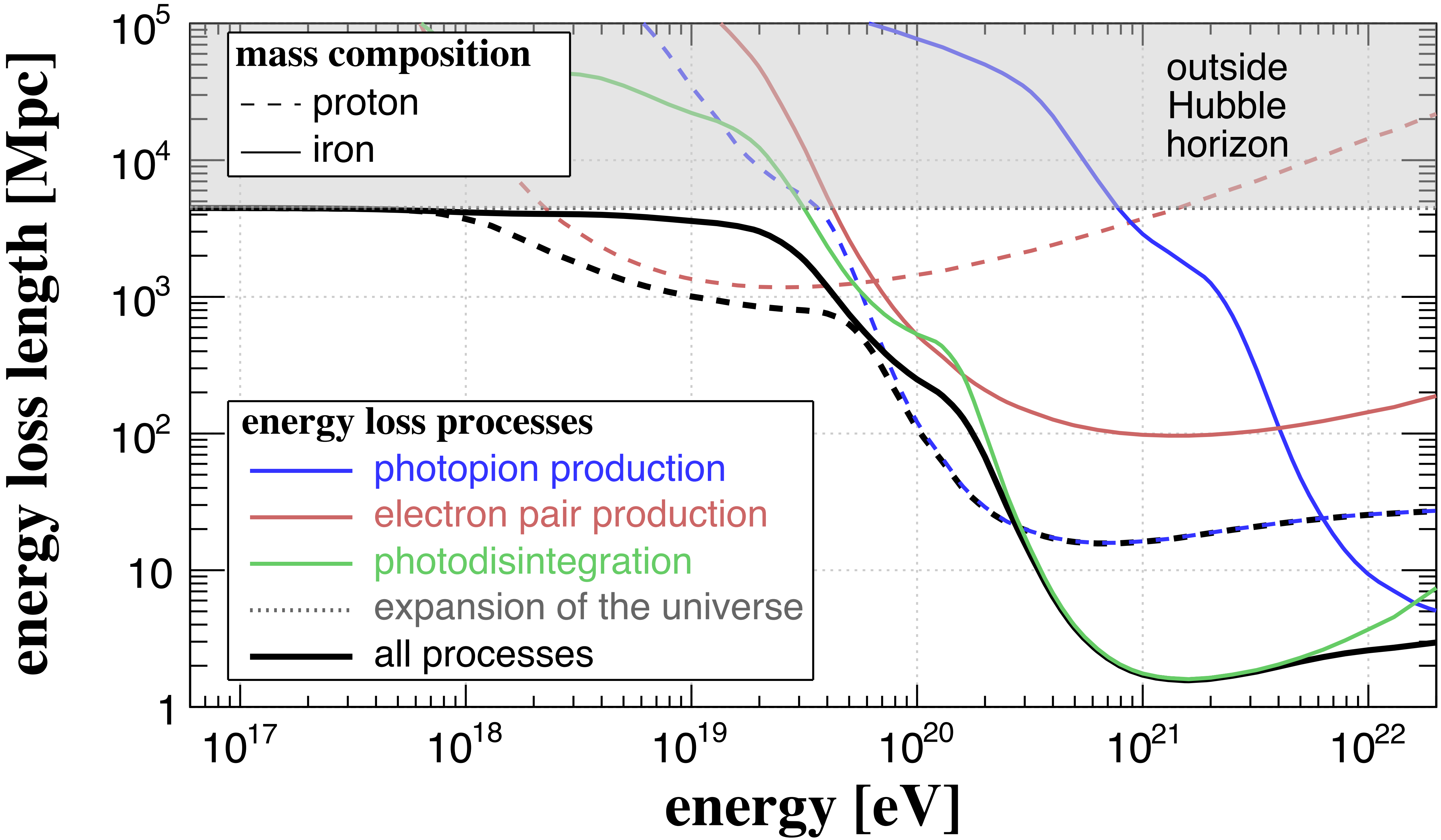
$$\frac{dE_g}{dE} = (1+z)\exp\left(\int_0^z dz' \left|\frac{dt'}{dz'}\right| \frac{\partial}{\partial E_g} b(E_g, z')\right)$$

Syrovatskii variable

$$\lambda(E,z,B) = \sqrt{\int_0^z dz' \left|\frac{dt}{dz'}\right| \frac{D(E_g,z',B)}{a^2(z')}}$$

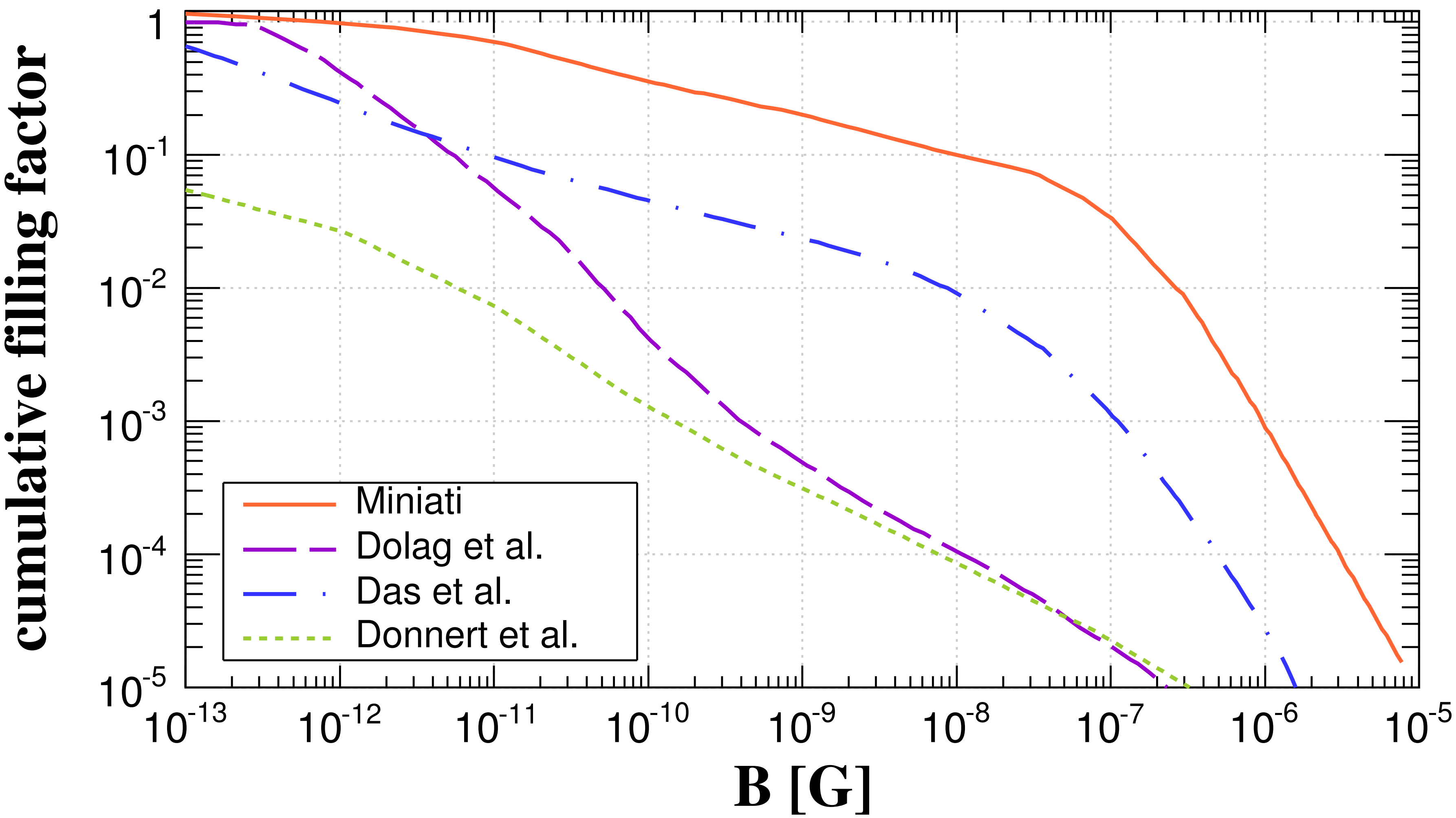
- Syrovatskii variable defined in units of length
- this is equal to the **magnetic horizon** of the particle

energy losses



- only relevant energy loss process below Z EeV: adiabatic
- energy losses due to electron pair production, pion production, photodisintegration can be neglected below Z EeV

extragalactic magnetic fields



Miniati, MNRAS 337 (2002) 199

Dolag et al. JCAP 01 (2005) 09

Das et al. ApJ 682 (2008) 29

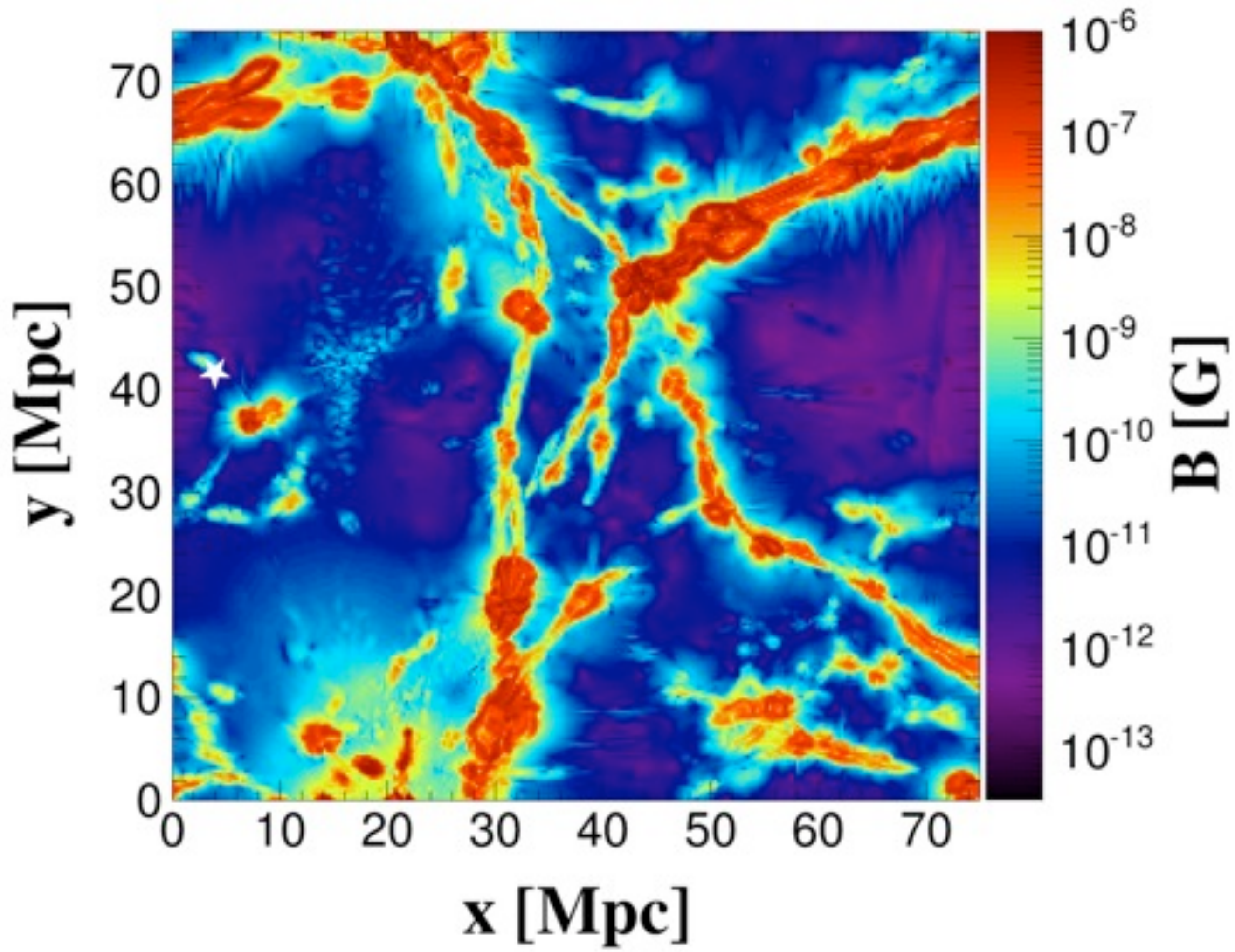
Donnert et al. MNRAS 392 (2009) 1008

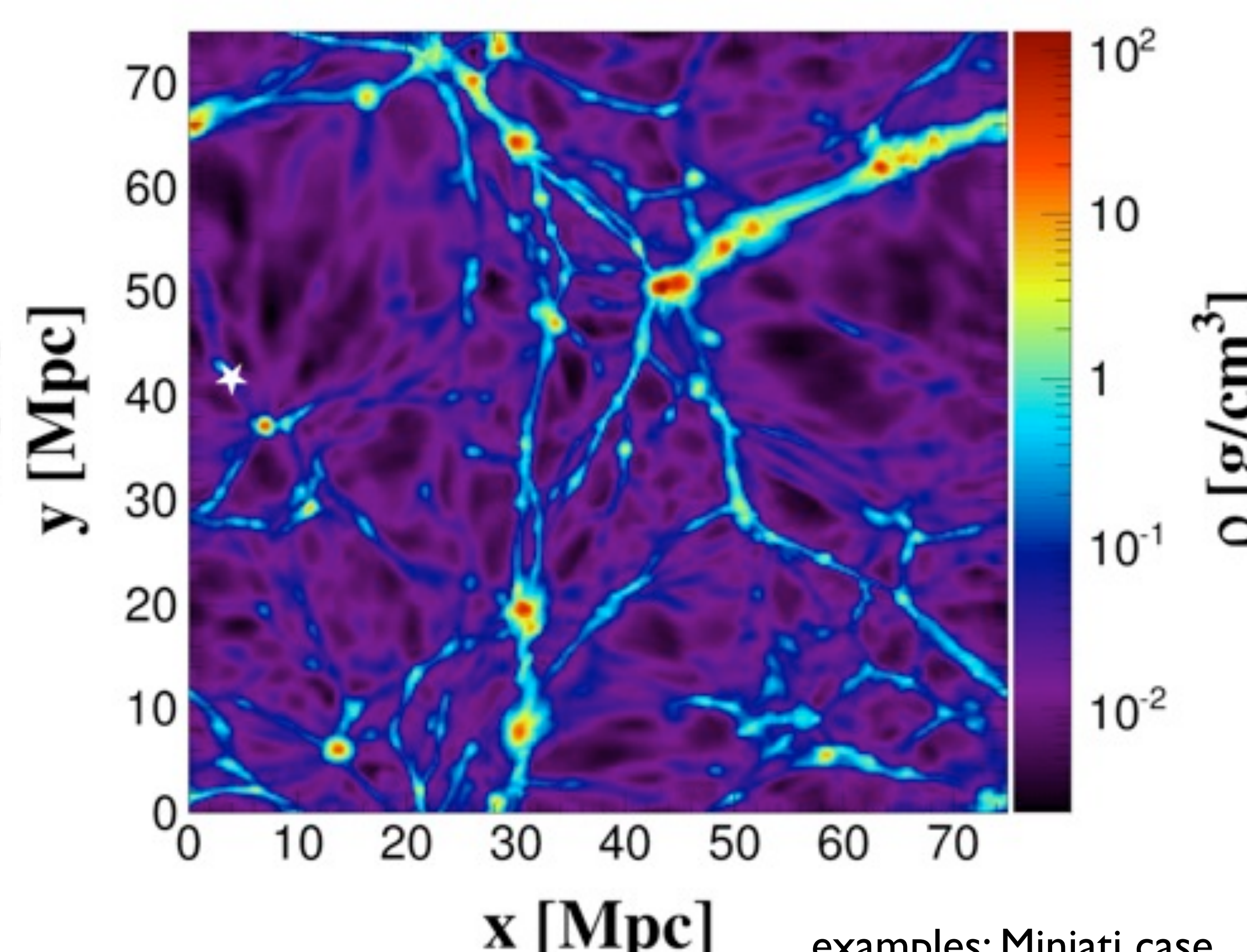
- four models considered
- filling factors = complementary cumulative distribution function (1-CDF)
- probabilities calculated from filling factors distribution

	Miniati	Dolag et al.	Das et al.	Donnert et al.
<B> [G]	1.8×10^{-8}	5.5×10^{-11}	1.2×10^{-9}	6.3×10^{-11}
B_{rms} [G]	1.7×10^{-7}	1.5×10^{-8}	5.7×10^{-8}	1.7×10^{-8}

cosmological simulations

- solving MHD equations
- magnetic field seed can be provided at a given (very high) redshift
- or magnetic field is estimated from density (only hydrodynamics + Biermann battery)
- magnetic fields probably correlated with matter distribution





examples: Miniati case

magnetic suppression

suppression factor

$$G(x) = \frac{j(E)}{j_0(E)}$$

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universal spectrum

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$$x \equiv \frac{E}{\langle E_c \rangle}$$

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$$X_s = \frac{d_s}{\sqrt{R_H l_c}}$$

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$j_0(E)$: universal spectrum

$$X_s = \frac{d_s}{\sqrt{R_H l_c}}$$

d_s: average source separation

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average source separation

coherence length of the field

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$$X_s = \frac{d_s}{\sqrt{R_H l_c}}$$

d_s: average source separation

l_c: coherence length of the field

$$x \equiv \frac{E}{\langle E_c \rangle}$$

critical energy

$$E_c(z, B) = cZeB(z)l_c(z) \approx 0.9Z\left(\frac{B}{\text{nG}}\right)\left(\frac{l_c}{\text{Mpc}}\right)\ \text{EeV}$$

suppression factor

average source separation

$$G(x) = \frac{j(E)}{j_0(E)} = \exp\left(\frac{(aX_s)^\alpha}{x^\alpha + bx^\beta}\right) \qquad X_s = \frac{d_s}{\sqrt{R_H l_c}}$$

universal spectrum

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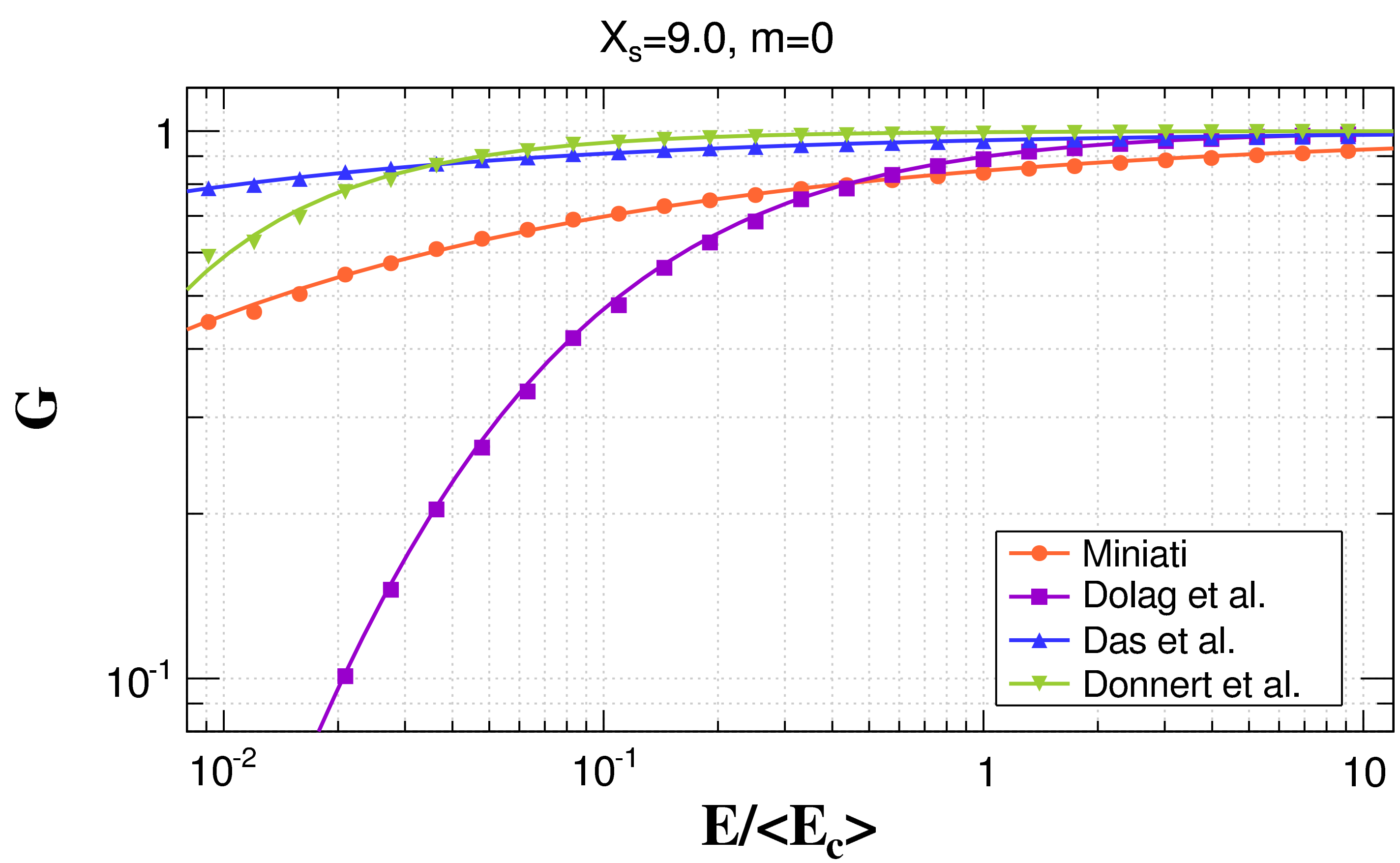
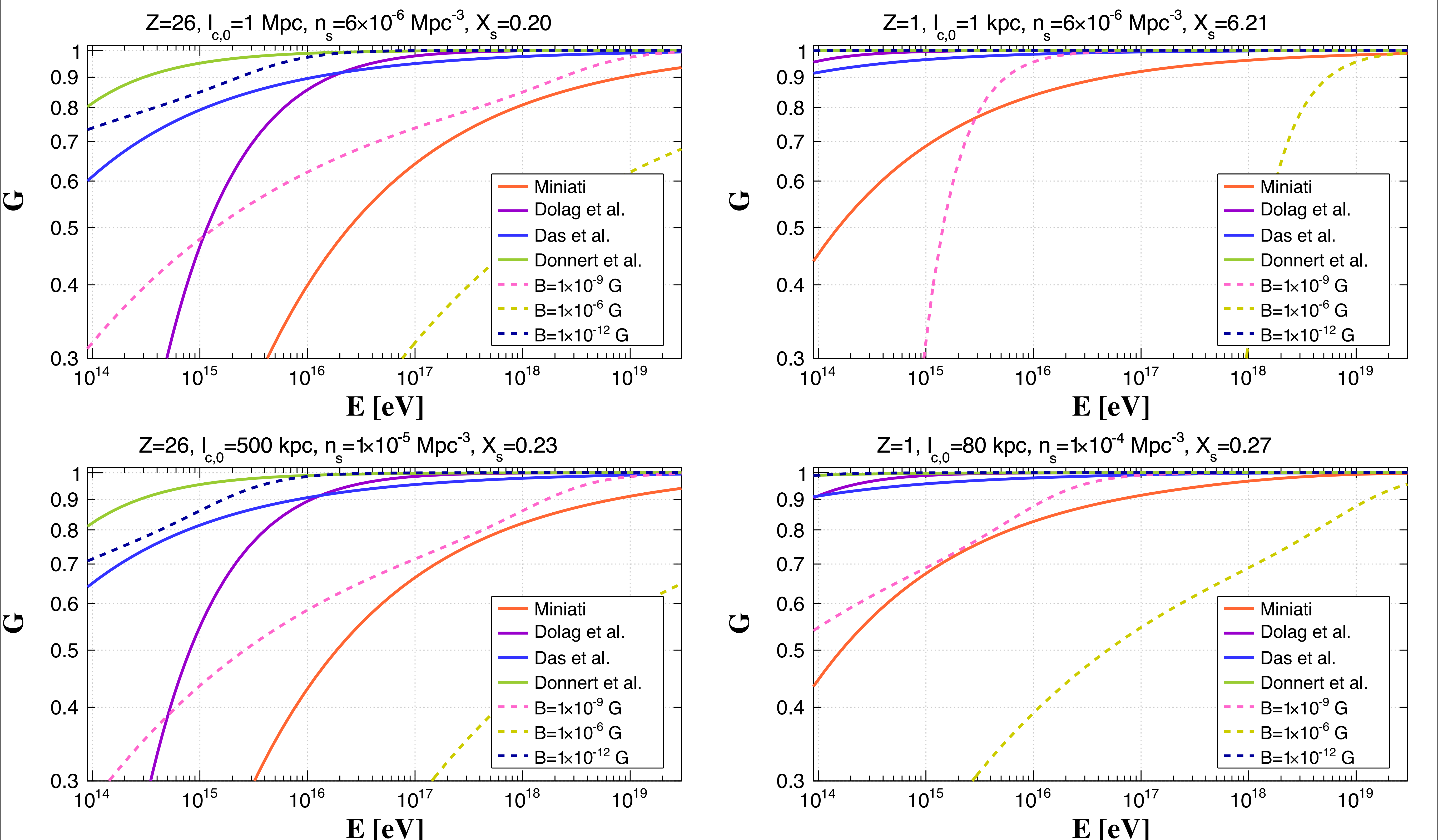
RAB & Sigl. arXiv:1407.6150

- expression to "fit" magnetic suppression at "low" energies first used by Mollerach & Roulet '13
- propagation time of cosmic rays comparable to the Hubble radius
- α, β, a and b are taken from the best fit of G

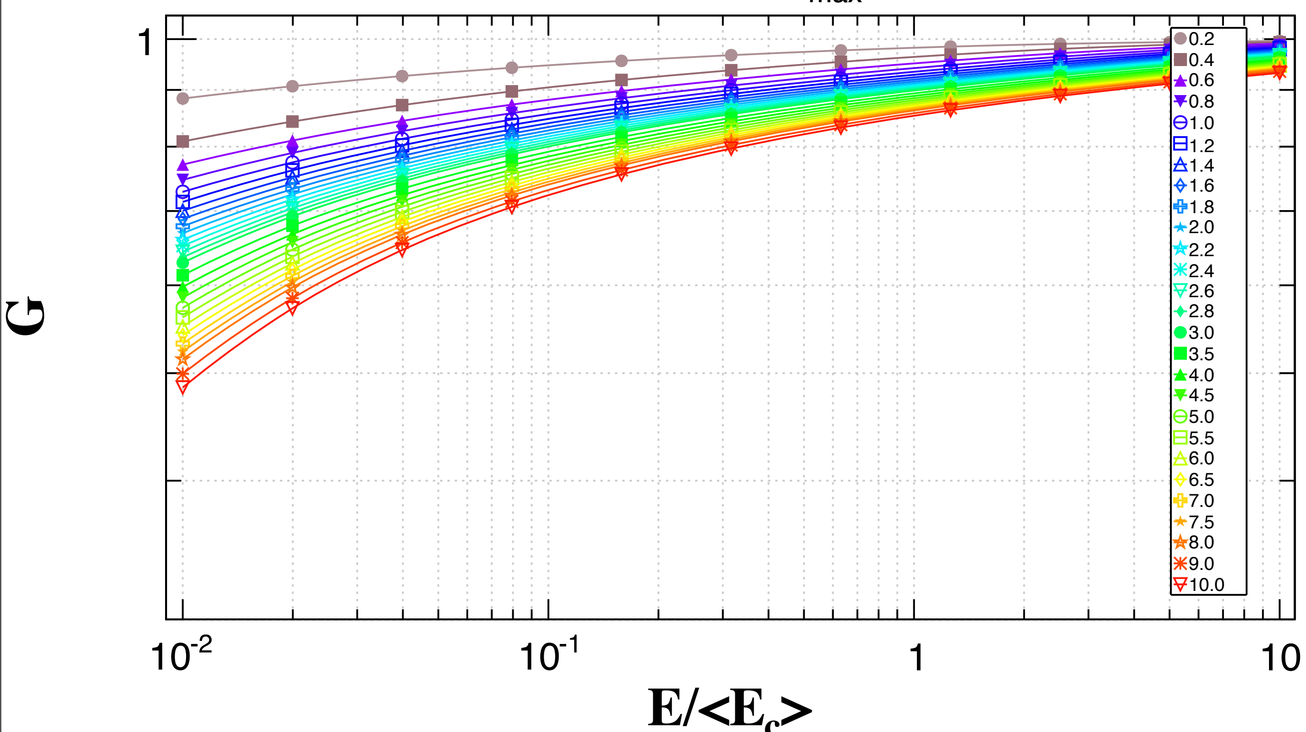


magnetic suppression: examples

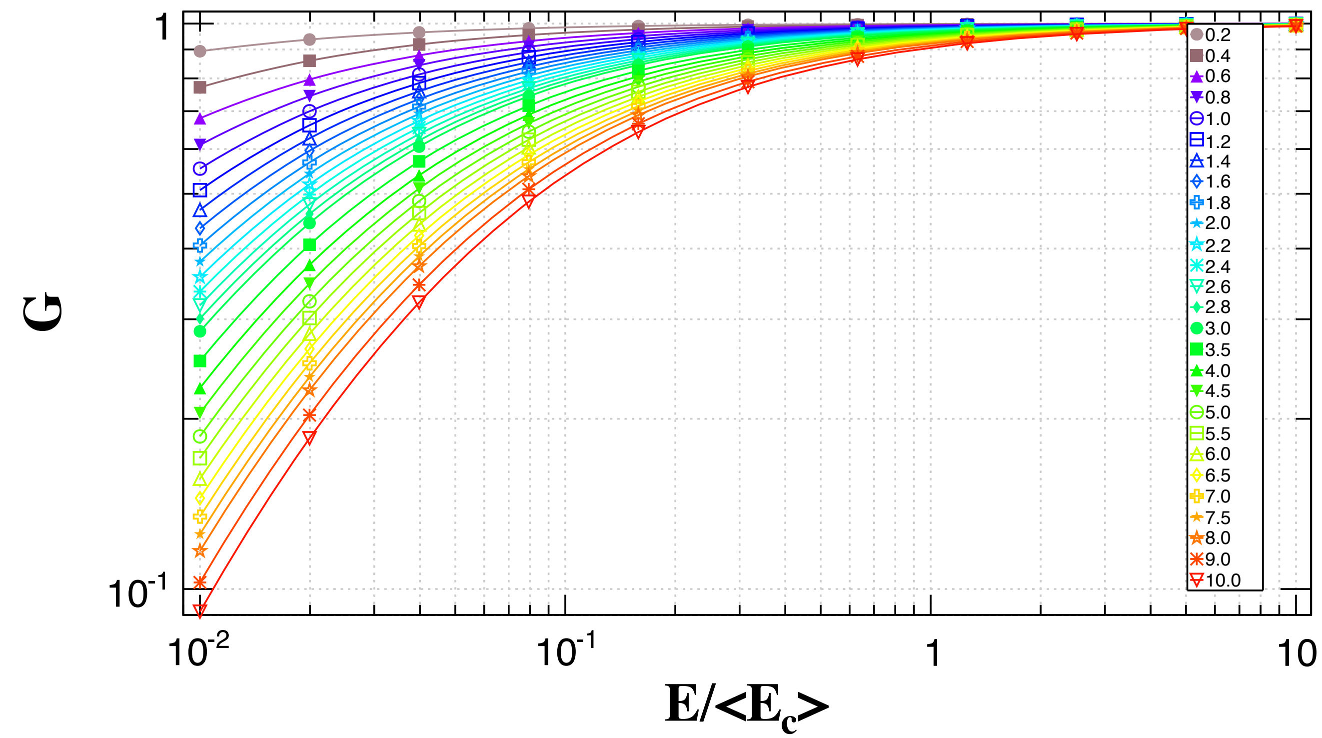


magnetic suppression: examples

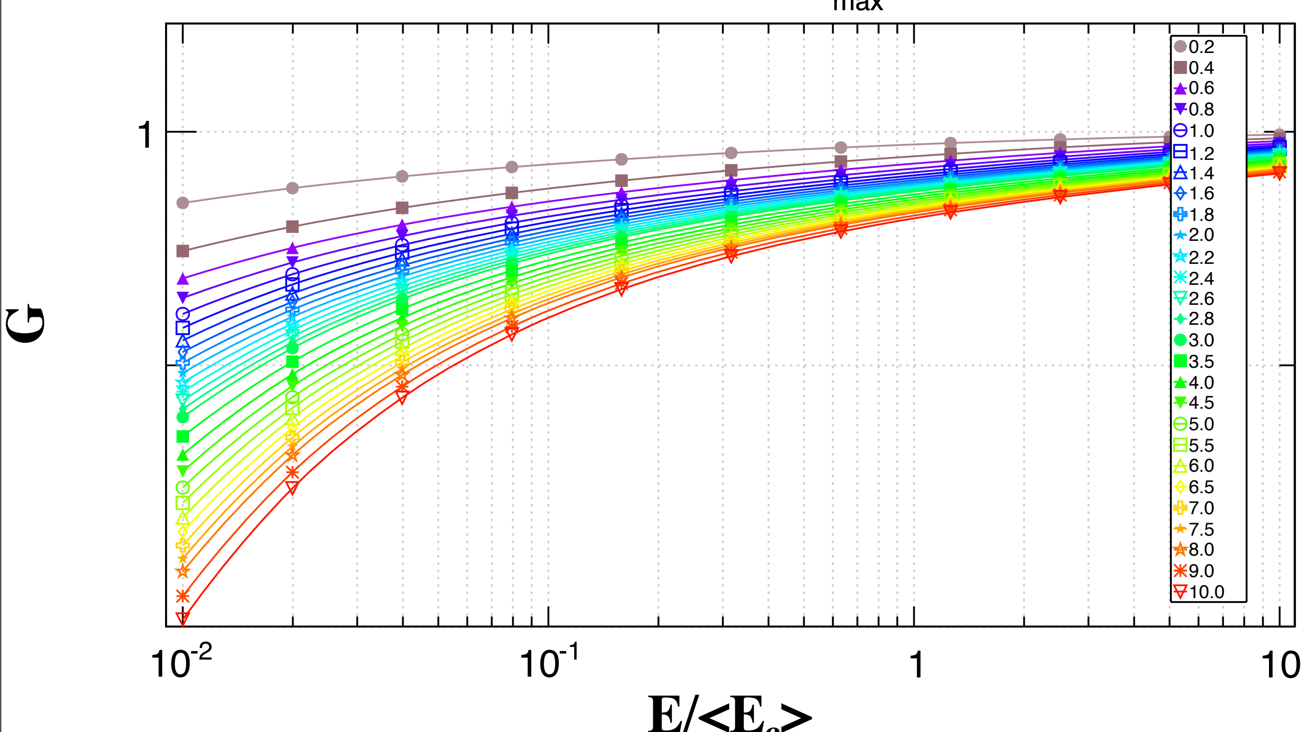
Miniati - m=1, γ=2.0, z_{max}=4.0



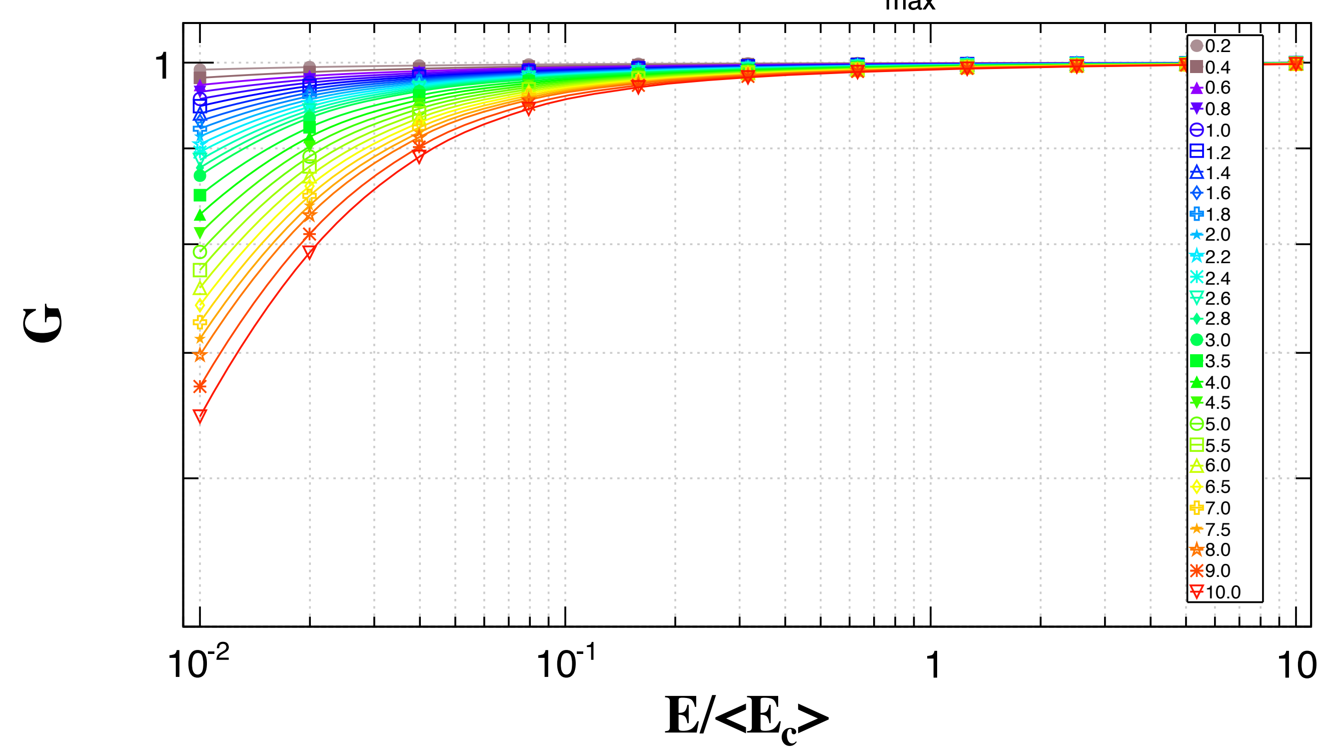
Dolag et al. - m=1, γ=2.0, z_{max}=4.0

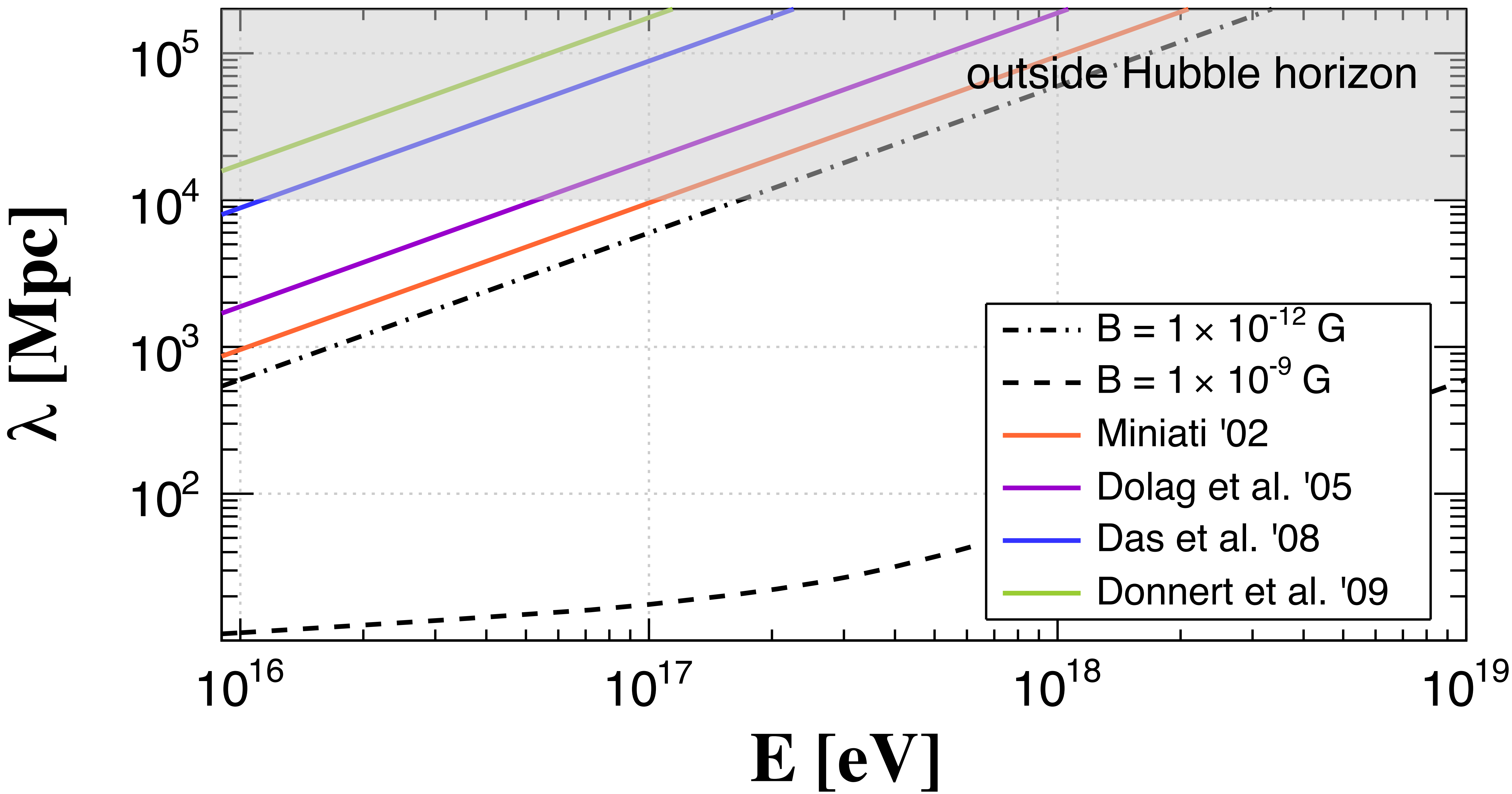


Das et al. - m=1, γ=2.0, z_{max}=4.0

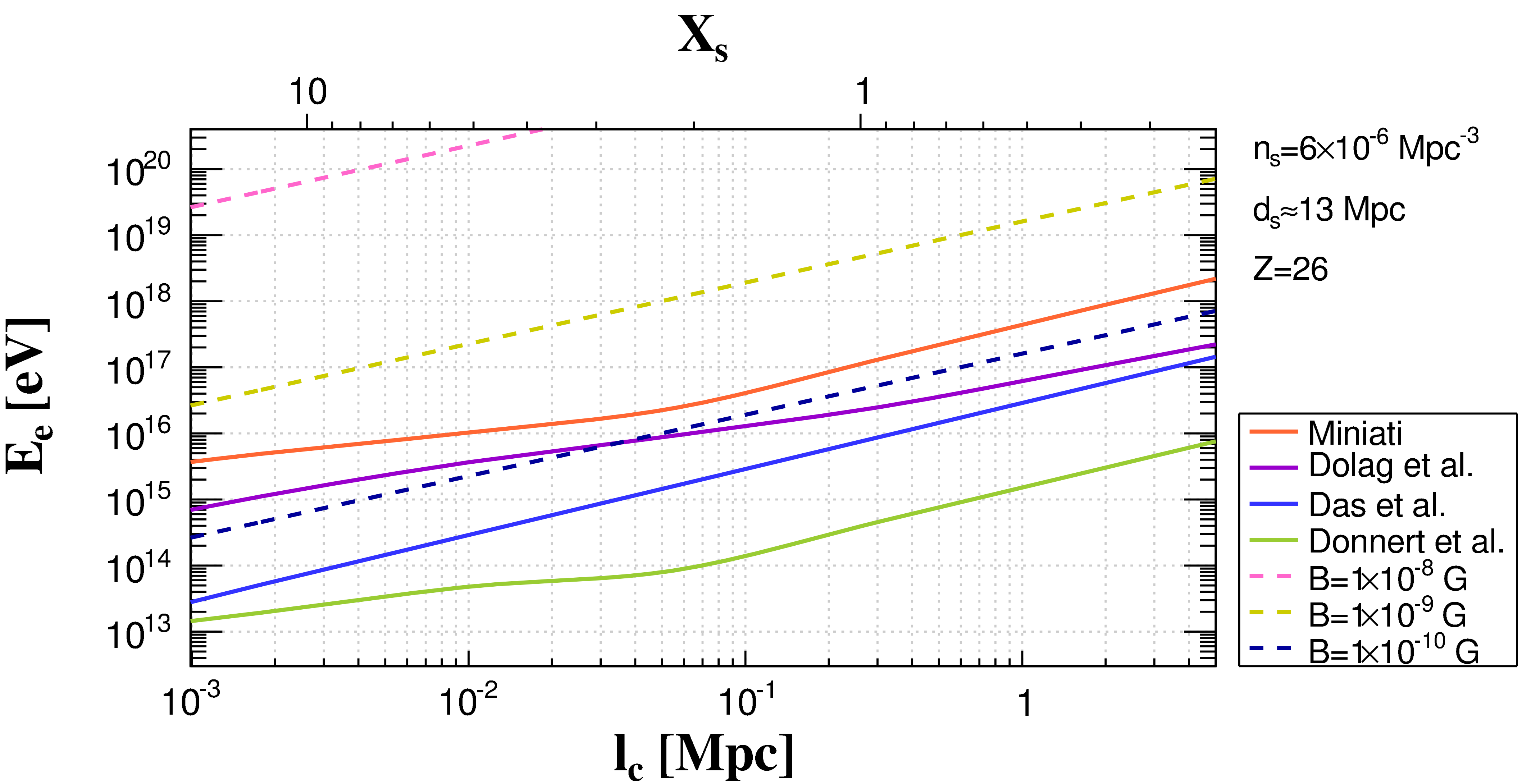


Donnert et al. - m=1, γ=2.0, z_{max}=4.0




outside Hubble horizon
B = 1 × 10^-12 G
B = 1 × 10^-9 G
Miniati '02
Dolag et al. '05
Das et al. '08
Donnert et al. '09
λ [Mpc]
E [eV]
10^2
10^3
10^4
10^5
10^16
10^17
10^18
10^19

magnetic suppression: upper limit



- $G(E_e) = 1/e$: suppression of the flux to 1/e of its former value

$$E_e^{\alpha} + bE_e^{\beta}\langle E_{c,0}\rangle^{\alpha-\beta} = (aX_s\langle E_{c,0}\rangle)^{\alpha}$$

- suppression start to become pronounced for $E<10^{17}$ eV for heavy nuclei
- extragalactic CR spectrum extends to lower energies → but is probably dominated by contribution of other source populations

the hard spectra “problem”

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- combined spectrum-composition fits of Auger data suggest hard spectral index ($\gamma < 2$) (*Taylor ’13, Aloisio+ ’13*), which has been referred to by some authors as the hard spectra “problem”

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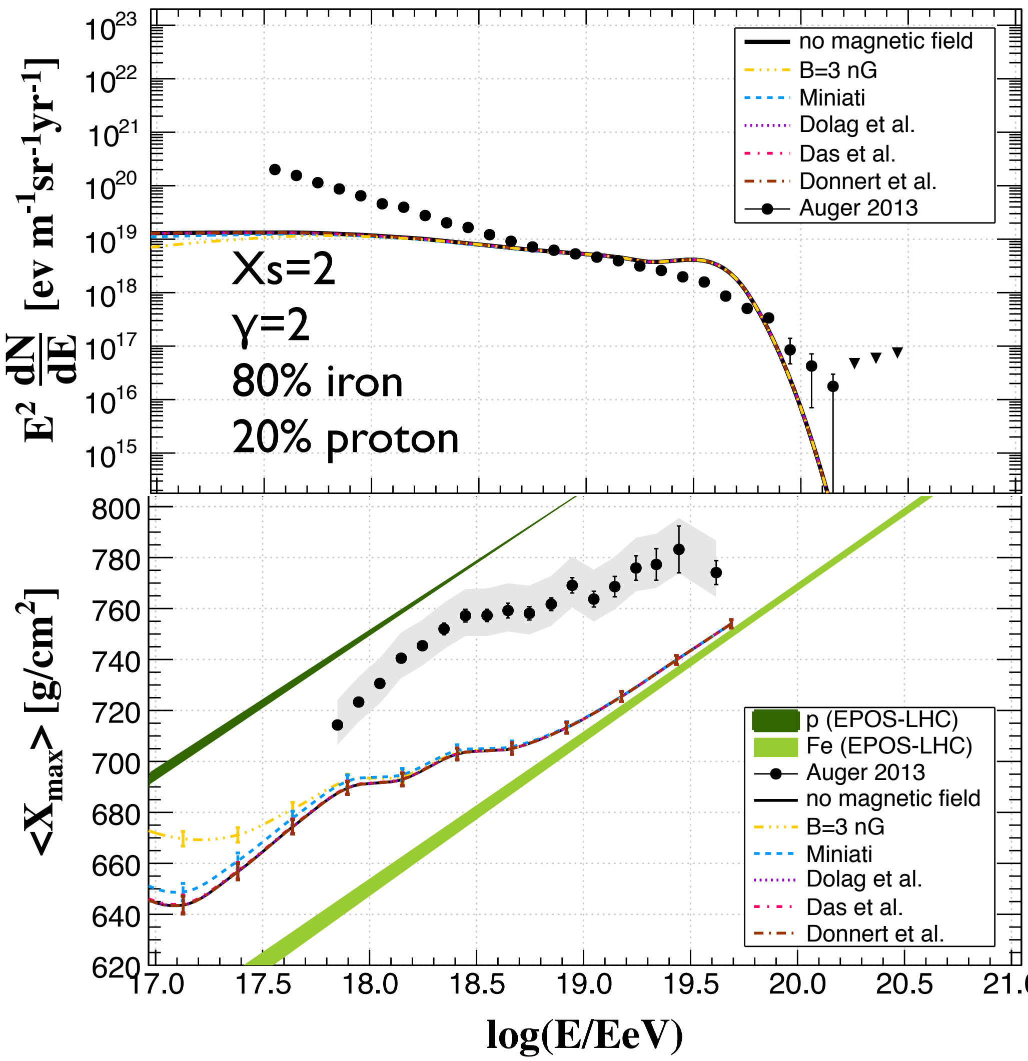
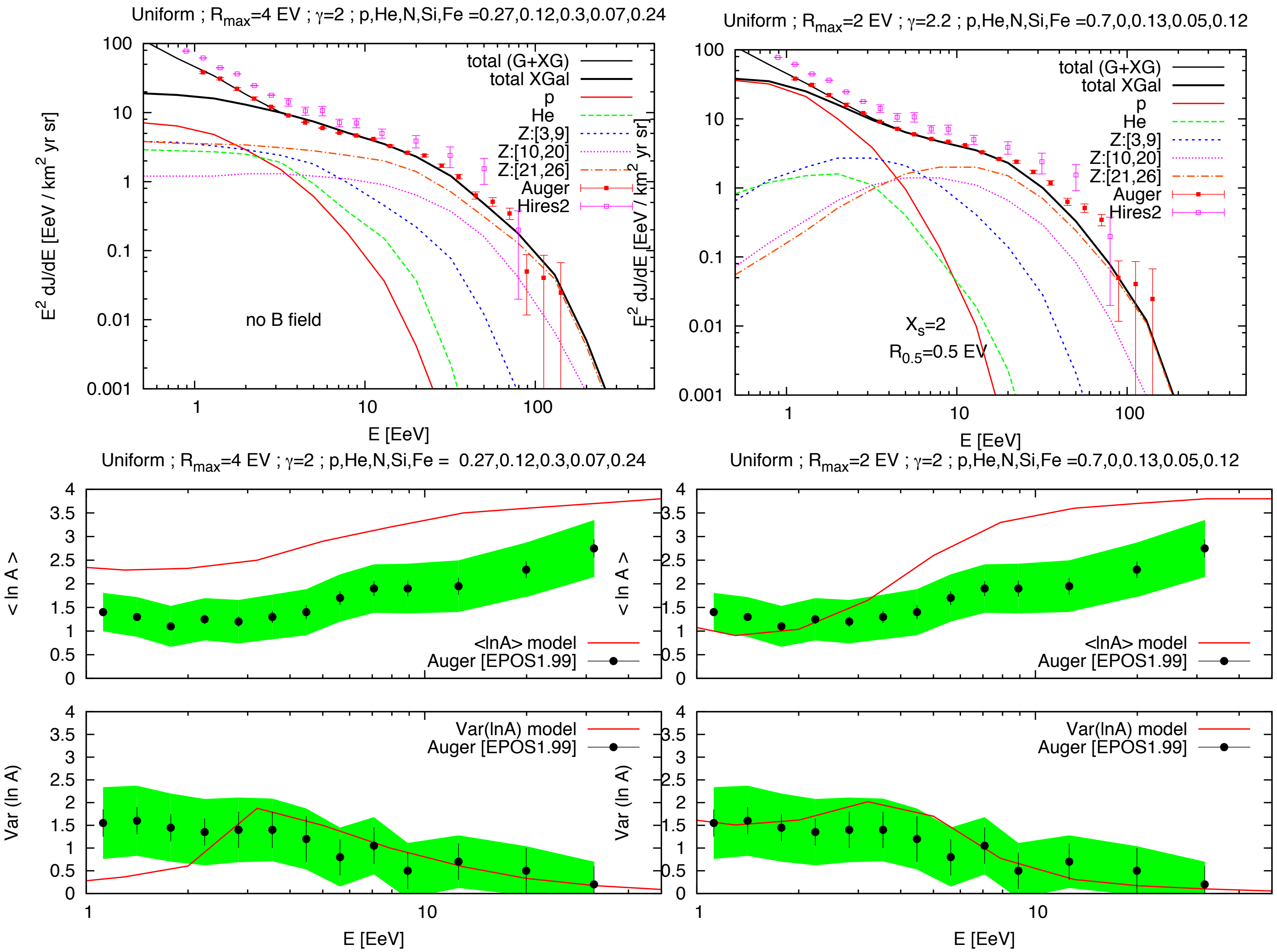
- if this suppression sets in below 10^{18} eV hard spectral indexes are still needed

the hard spectra “problem”



simulations done with CRPropa 3.0



RAB et al. arXiv:1307.2643 **Mollerach & Roulet JCAP 10 (2013) 013**

- strong suppression → softer spectral indexes (compatible with Fermi acceleration)
- with realistic models of extragalactic magnetic fields → hard spectral indexes still required
- weak suppression → contribution of far away sources may be relevant below 1 EeV
- local sources may dominate → 3D simulations with full Monte Carlo approach may be needed

summary & outlook

- semi-analytical calculation of the cosmic ray spectrum below ~ $Z \times 10^{18}$ eV considering inhomogeneous magnetic fields from cosmological simulations
- we have obtained a parametrization of the suppression due to the magnetic horizon of the particles assuming several models of extragalactic magnetic field
- the extragalactic CR spectrum can extend down to low energies
- magnetic suppression was postulated to explain the hard spectral index problem
- our results indicate that in realistic magnetic field scenarios the magnetic suppression would set in at very low energies → hard spectral indexes still required
- caveat: effects of nearby sources → 3D simulations needed (how reliable are the models for the extragalactic magnetic field?)

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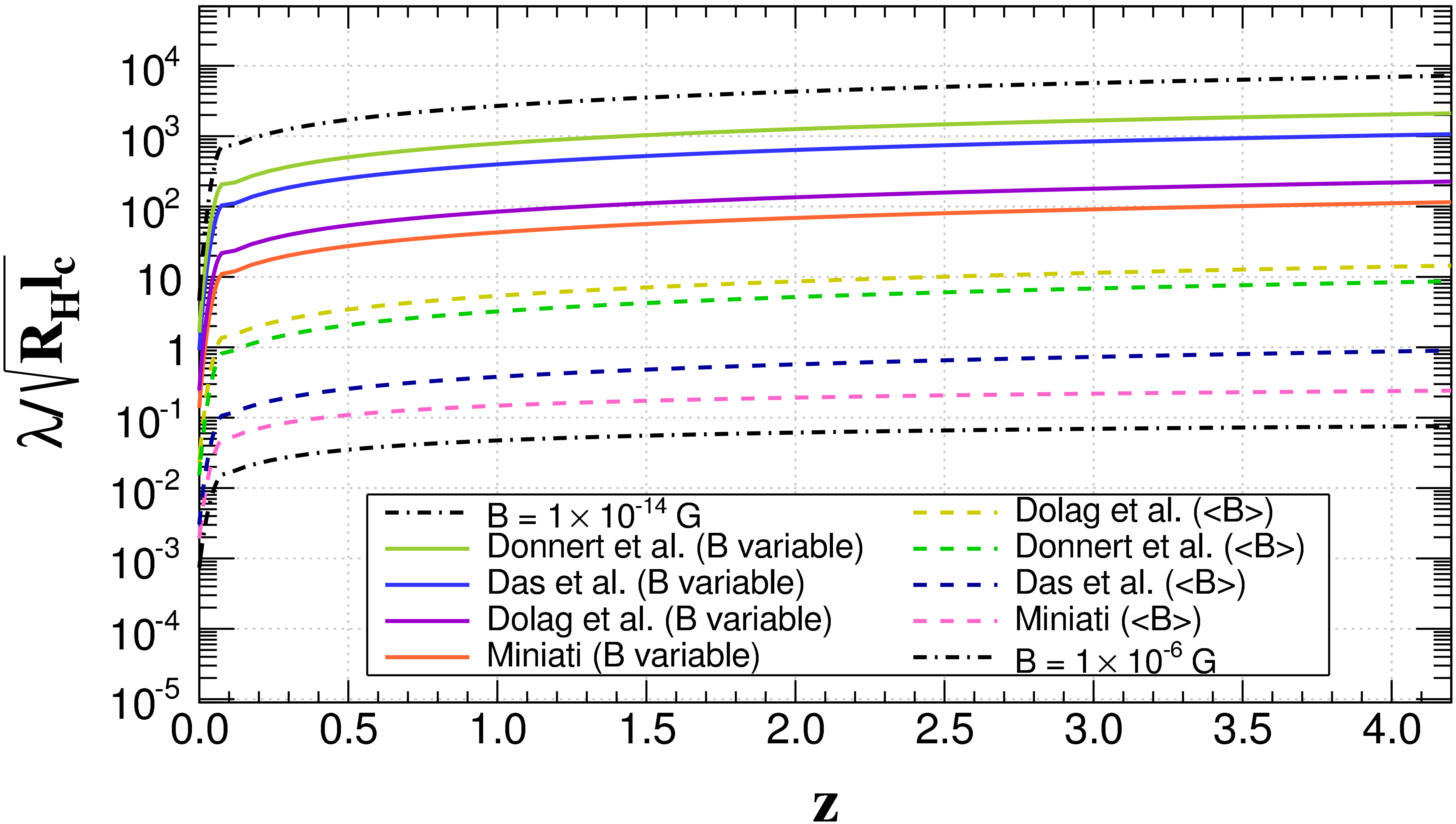
Thank you!

magnetic horizon



best fit parameters